The Probable Energy Loss of Electrons in Matter

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The probable energy loss of electrons passing through thin mica, Al, Cu, Zn, Ag, Cd, and Sn have been measured, using a double coil, magnetic lens beta-ray spectrometer. As the monochromatic electrons, we have used the photo-conversion lines produced in a lead radiator by the gamma-rays of Radium, Zn^{65}, and Co^{60}, The results obtained indicate that the probable energy loss of electrons of moderately high energies shows reasonable agreement with the theoretical values calculated according to the formula of Landau.

I. INTRODUCTION

The probable energy loss of electrons in matter has been studied by many workers since the theoretical treatment by Bohr[1] in 1915. A summary of his theory and comparison with experiments of White and Millington[2] have been given by Rutherford and others[3]. The probable energy loss has been calculated recently by Landau[4] and the average energy loss has been given by Bethe[5] and Bloch[6]. Although the energy struggling of electrons in matter has been of interest in many experiments, there has been no good measurement since the early work of White and Millington.

Recently, using the beta-ray spectrometer, Birkhoff[7], Warshaw and Chen[8] have measured the probable energy loss of electrons in mica sheet with the monochromatic conversion line of the 0.663-Mev gamma-ray from Ba137. The results of Birkhoff concerning the energy distribution of electrons passing through mica were in disagreement with the formula of Landau, but those of Warshaw and Chen showed agreement with it.

In the present work, undertaken to obtain more information on the probable energy loss of electrons in many elements at the moderately high energies, we have tried to measure these values for eight elements, mica, Al, Cu, Zn, Ag, Cd, and Sn, with the monochromatic photo-conversion lines produced in a lead radiator by the gamma-rays from Radium, Zn^{65}, and Co^{60} using a double coil, magnetic lens beta-ray spectrometer of about 2.4 percent resolving power, and we compared the results obtained with the values expected theoretically.

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II. DESCRIPTION OF SPECTROMETER

The spectrometer used in the present work is shown in Figs. 1 and 2. The design is similar to that employed by previous workers[9)~13)]. The instrument is mounted with its axis parallel to the magnetic field of the earth, and in order to minimize the scattering and to separate the positive and negative electrons, the spiral baffle with four wings of 50 cm in length is set in the middle part of the chamber as shown in Fig. 2. Double lens coil is used to minimize the spheri-cal aberration. Non-ferromagnetic materials have been used throughout to preserve linearity. The trajectories of electrons and the method of detemining the axis of the chamber with the lens coil have been reported[14)]. The spectro-chamber, 13.5 cm in diameter and 115 cm long, is evacuated by means of a four stage mercury dif-fusion pump backed by a mechanical pump. Radioactive source is mounted with small brass sick in the chamber just behind a lead radiator, which is maintained on the cotton cross wire. The detector used was an end-window G-M counter with mica window of 3mg/cm^2 thickness. The counter was connected to a scale-of-64 recording circuit.

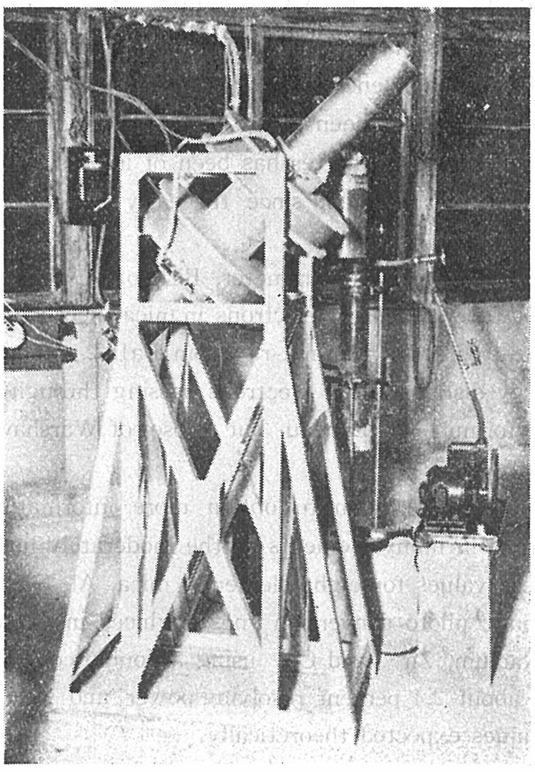

Fig. 1. The double coil, magnetic lens beta-ray spectrometer, aligned with its axis parallel to the magnetic field of the earth.

The coil for producing the magnetic field consists of two sets of 1850 turns of No. 12 double cotton-covered copper wire. Each complete coil has an inside radius

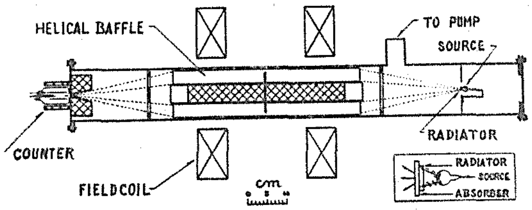

Fig. 2. Diagram of the spectro-chamber.

of 23.5 cm and an axial length of 8 cm with the distance of 20 cm apart each other. When the full power is used with 200 volt across the coil, a focal length of 25 cm is obtainde for electrons of 2.4-Mev energy.

For the current stabilizer which is adequate to control the coil current, we have constructed that of Lawson and Tylor type[5], because it has a good stabilization ratio and is easily operated to shift the coil current into a new stabilized value. The general figuers of the stabilizer circuit are shown in Figs. 3 and 4. Its principle of action is the same as those described by Lawson and Tylor, except that 6SN7 and photo-cell 17G1 are used. By this stabilizer circuit, we are able to maintain the constancy of the coil current within 1/50,000 for a long time and to shift into a new stabilized value within 10 seconds.

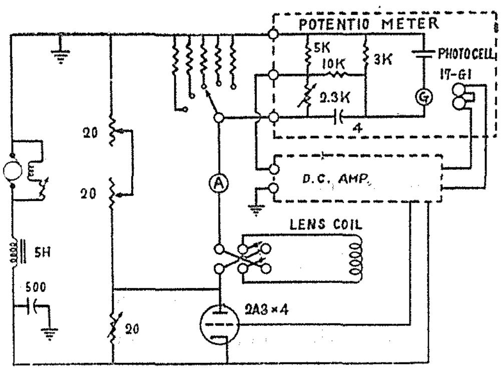

Fig. 3 Stabilizer circuit.

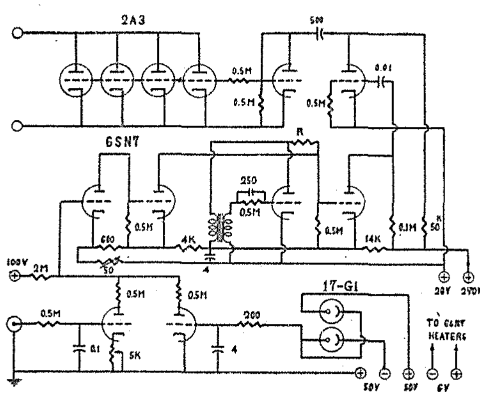

Fig. 4. D-C amplifier in stabilizer circuit.

III. RESULTS AND DISCUSSIONS

In the present work, the electrons which have the monochromatic energy were obtained by the spectrum of photo-conversion electrons produced in a lead foil. Four monochromatic electrons used are shown in Table 1.

The ıadioactive sources of Zn^{65} and Co^{60} used were prepared from radioactive solutions supplied from Oak Ridge. Evaporation residuum of the cobaltaous chrolide solution of about 2 millicuries equivalent intensity, and of the zinc chloride solution of about 1 millicurie equivalent intensity, sealed in a thin glass sphere of 3 mm in

Table 1. Four photo-conversion lines used in the work.

Sources		$h\nu$ (Mev)	K-electrons	
			(Mev)	β
RaB	(18)	0.3499	0.2624	0.7508(β_1)
RaC	(18)	0.6067	0.3192	0.8684(β_2)
Zn^{65}	(16)	1.114	1.0266	0.9432(β_3)
Co^{60}	(17)	1.3315	1.2449	0.9567(β_4)

Binding energy of K-electron of lead is taken as 37.52-Kev.

diameter,were used as the gamma-ray sources.

In addition to the photo-conversion lines generated in a lead by the gamma-rays and the annihilation radiation, a broad distribution of the Compton electrons was also observed in the spectrum of these sources. To permit an accurate determination of the energies of the photo-electrons ejected from the radiator, attention must be given to the effect of the radiator thickness. The positions of the points of the maximum intensity with various radiator thickness were measured and the results obtained are shown in Fig. 5. As the energies of these gamma-rays have been

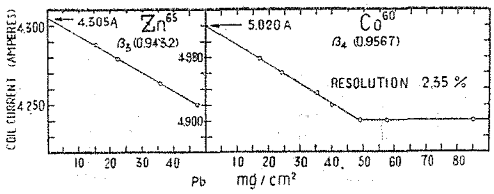

Fig. 5. Values of coil current corresponding to the peak positions of the photo-conversion lines as a function of suface density of a lead radiator.

known accurately, the spectrometer constant k was estimated from the coil current i at the zero thickness of radiator foil, where k is equal to p/i and p is the energy of photo-electron, which express the linearity between the energy of the focused electron and the coil current. The value of k was estimated as 1124.5 gauss-cm/amp. from Fig. 5. When we used the element, whose atomic number is less than 50, as an radiator foil, no photo-conversion line and no Compton electoron was observed at the peak position of the photo-conversion line produced in a lead radiator. It means that the Compton electrons of the absorber whose atomic number are less than 50 give no contribution to the photo-peaks generated in a lead radiator. Therefore we used these photo-peaks of lead radiator as the monochromatic electrons which should be shifted to the lower momentum after passing through the absorber set just behind it.

In addition to the above two photo-peaks from Zn^{65} and Co^{60}, we used more two lines from Radium. But in this case, the effect of the Compton electrons ejected from the absorber was not eliminated in the photo-peaks from a lead radiator. The inclinations of the Compton levels which consist of the background in the peak displacement were measured and estimated as 25 and 10 percent for β_1 and β_2 respectively. These corrections have been given in the observed values shown in Tables 2 and 3.

Table 2. The measured values of stopping power I of elements.

Elements	Thickness μ (cg/cm²)	Stopping power I For β_2	For β_3	For β_4
Al	1.385	57.0	49.1	49.1
Ni	1.546	52.0	47.7	47.7
Cu	1.831	52.2	49.1	46.1
Zn	1.297	—	47.6	47.6
Ag	1.490	48.8	42.2	45.2
Cd	1.146	44.0	39.0	39.0
Sn	1.163	—	43.6	43.6

Thickness of lead radiator is 3.206 cg/cm².

Table 3. The measured values of stopping power I of mica.

Thickness μ (cg/cm²)	Stopping power I For β_1	For β_2	For β_4
0.403	70.3	42.2	—
0.701	72.3	56.2	48.2
1.057	84.9	58.3	48.2
1.403	84.2	60.1	48.2

Thickness of lead radiator is 3.720 cg/cm².

Two examples of the peak shift observed are shown in Fig. 6 and the numeri-

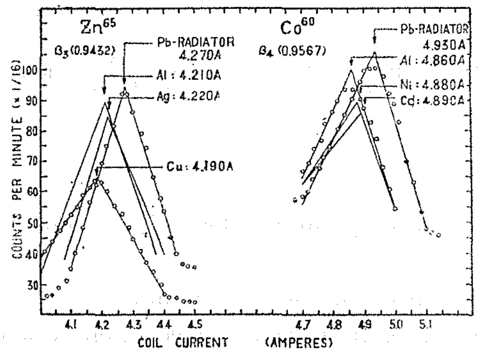

Fig. 6. Probable energy loss of electrons in matter.

cal results are tabulated in Tables 2 and 3, in which I is the stopping power of these elements and is equal to $\Delta(H\rho)/\mu$, where μ is the surface density of these elements in units of cg/cm^2. The experimental errors in these measurements of peak shifts were estimated within $\pm 3H\rho$. In the case of the gamma-rays from Radium, the correction factors for the Compton electrons of the absorbers were estimated as -7.5 $H\rho$ and -5.0 $H\rho$ for the electrons of β_1 and β_2 respectively.

These experimental values of the stopping power I were compared with the theoretical values. In the computation of the theoretical values, we used the following formulae :

Bohr formula,

$$\Delta E = \frac{2\pi e^4 N_0\sigma}{mv^2} \cdot \frac{z}{A}\left[\log_e \frac{(1.123)^2 \cdot C^2 \cdot \sigma \cdot z}{4\pi A} + \log_e \frac{\beta^2}{1-\beta^2} - \beta^2 - 2C\right]$$

Bethe-Bloch formula,

$$\Delta E = \frac{2\pi e^4 N_0\sigma}{mv^2} \cdot \frac{z}{A}\left[\log_e \frac{2(m_0c^2)\beta^4}{E^2 \cdot Z^2 \cdot (1-\beta^2)} + 1 - \beta^2\right],$$

Landau formula,

$$\Delta E = \frac{2\pi e^4 N_0\sigma}{mv^2} \cdot \frac{z}{A}\left[\log_e \frac{4\pi e^4 N_0\sigma\, e^{-\beta^2}}{E^2(1-\beta^2)} \cdot \frac{A}{z} + 0.37\right],$$

where N_0 is the Avogadro's number ; Z, the atomic number ; A, the atomic weight ; σ, the surface density in g/cm^2 ; and E, the binding energy of K-electron. The value of a constant C in the Bohr formula was chosen as 41.1 by Rutherfored according to the experimental values of White and Millington.

These formulae can be reduced to the following simple forms which are expressed in units of $H\rho$, using the known values of constants.

Bohr-White-Millington formula,

$$I\beta^3 = 5.10\frac{z}{A}\left[14.1 - \beta^2 + \log_e \frac{\beta^2}{1-\beta^2}\ \mathrm{iog}_e\, \mu + \log_e \frac{z}{A}\right],$$

Bethe-Bloch formula,

$$I\beta^3 = 5.10\frac{z}{A}\left[22.75 - \beta^2 + \log_e \frac{\beta^4}{1-\beta^2} - \log_e z^2\right],$$

Landau formula,

$$I\beta^3 = 5.10\,\frac{z}{A}\left[16.30 - \log_e \frac{e^{-\beta^2}}{1-\beta^2} + \log_e \mu + \log_e \frac{z}{A}\right],$$

where μ is the surface density in units of cg/cm^2.

The measured and theoretical values, which were calculated with the above simple forms, plotted against the elements are shown in Fig. 7, while these values plotted against the surface density of mica are shown in Fig. 8. B-W-M, B-B, and L curves in these figures show the values calculated by the formula of Bohr-White-Millington, Bethe-Bloch, and Landau respectively.

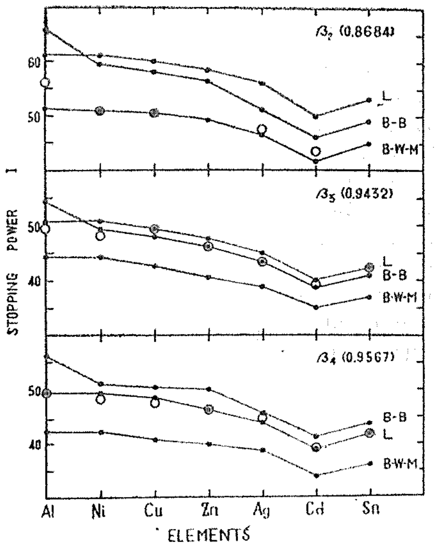

Fig. 7. Experimental and theoretical values of the stopping power I, plotted against the elements, where the measured values are shown in open circles.

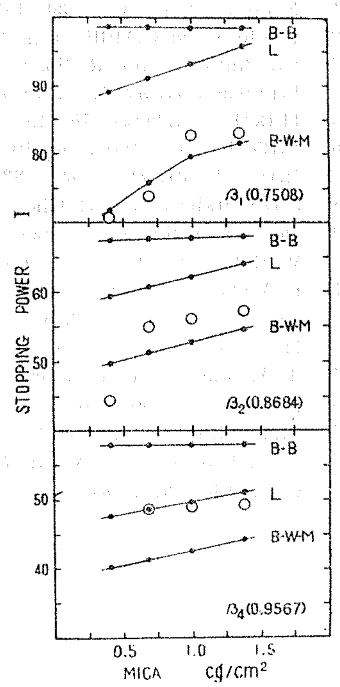

Fig. 8. Experimental and theoretical values of the stopping power I, plotted as a function of the surface density of mica, where the measured values are shown in open circles.

The results obtained with the electrons β_3 and β_4, which have no correction for the Compton electrons of absorber, show reasonable agreement with the formula of Landau. The discrepancies of the measured values with the Landau formula for the electrons of β_1 and β_2 seem greater than the experimental errors: these may be attributed to the Compton electrons of the absorbers. It is noted that the observed probable energy loss of electrons in matter expressed by the formula of Bohr with good agreement, if we assume the constant C in his formula as the function of the energy of electrons.

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